

Electromagnetic interference from plasmas generated in meteoroids impacts

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Abstract. – It is shown that the plasma, generated during an impact of a meteoroid with an artificial satellite, can produce electromagnetic radiation below the microwave frequency range. This interference is shown to exceed local noise sources and might disturb regular satellite operations.

Introduction. – At the end of 1998, the first modules of the *International Space Station* will be put in orbit around the Earth and this should open new frontiers for life in space. The intensive use of the space makes necessary to know the potential risks. The threat from meteoroids is today well known and several authors have underlined the risks connected with the impact on a spacecraft (for a review, see [1]). However, the *Olympus* end-of-life anomaly [2] and the recent work of McDonnell *et al.* [3] put a new light on these issues. The *Olympus* failure is a paradigmatic example: in that case, the impact with a Perseid meteoroid may have generated electrical failures, leading to a chain reaction which culminated with an early end of the mission [2]. On the other hand, McDonnell *et al.* [3] showed that, if the plasma charge and current production during an impact are considered, meteoroid streams can be very dangerous, even during normal conditions. It should be noted that they considered only damages by direct discharges or current injection in circuits (*e.g.* via the umbilical) [3].

However, there are several other ways by which the plasma could interact with the spacecraft electronics. For example, it is useful to recall the work of Cerroni and Martelli [4], in which they showed that thermal forces in impact-produced plasmas could explain the magnetisation observed in the neighbourhood of lunar craters. Even if Cerroni and Martelli studied experimentally hypervelocity impacts of aluminium projectiles on basalt targets, it is possible to extend their work to general hypervelocity impacts.

Here, we show that a plasma cloud, generated during a hypervelocity impact of a meteoroid with an artificial satellite, can radiate electromagnetic energy below the microwave frequency range and, therefore, may disturb regular satellite operations.

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Meteoroids impacts. – It is well known that, during a hypervelocity impact, a fraction of the projectile and target materials is evaporated and even ionized [5]. A plasma cloud is then created almost instantaneously after the impact and expands into the surrounding vacuum. McDonnell *et al.* [3] found an empirical formula for the evaluation of charge Q produced during a hypervelocity impact. This equation, rearranged in order to emphasize the projectile dimensions and density, can be written as follows:

$$Q \simeq 3.04\delta^{1.02}r^{3.06}V^{3.48} \text{ [C]} \quad (1)$$

where δ is the meteoroid density [kg/m^3], r its radius [m] and V its speed [km/s]. In this paper, we consider, as a specific example, the Leonid meteoroid stream, that is the most dangerous stream known today owing to its high geocentric speed. Typical values of δ and V for Leonids are, respectively, 1000 kg/m^3 and 71 km/s .

In order to calculate the plasma characteristic parameters (Debye length λ_D and plasma frequency ν [6]), it is necessary to make further assumptions. The plasma cloud generated during an impact has been studied theoretically (*e.g.* [7]) and experimentally (*e.g.*, [4], [8], [9]). A projectile in an experimental facility reaches a speed up to about 10 km/s , far below meteoroids speeds, but data obtained in such experiments allow us to make some extrapolations.

Kadono and Fujiwara [8] recently investigated the expansion of the plasma cloud: they used nylon projectiles, with a speed range between 3 and 6 km/s , impacting targets made of different materials and found that the expansion velocity of the leading edge of the plasma cloud, u_{max} , is almost constant in time. The value is about twice that of the isothermal sound velocity (c_s):

$$u_{max} = \frac{2c_s}{\gamma - 1} \sqrt{\frac{\gamma}{3}} = \frac{2\gamma}{\gamma - 1} \sqrt{\frac{RT}{3\mu}} \quad (2)$$

where $\gamma = c_p/c_v$ is the constant ratio of specific heats, R is the universal gas constant [$R = 8.314510 \text{ J}\cdot\text{mol}^{-1}\text{K}^{-1}$], T is the gas temperature [K] and μ is the mean atomic weight of the plasma cloud. For a Leonid meteoroid, we can consider an almost complete composition of carbon and a plasma temperature of $30,000 \text{ K}$, taking into account that about 1% of the kinetic energy is partitioned into ionization [5]. For γ , a value of 1.7 is considered [8]. With these assumptions we obtain an expansion speed $u_{max} = 12.8 \cdot 10^3 \text{ m/s}$.

Moreover, we assume that the plasma cloud is almost hemispherical during first $20 \mu\text{s}$ and thus has a radius $\rho = 0.256 \text{ m}$. Then, the charge Q generated by an impact of a meteoroid with radius r , calculated with Equation (1), must be distributed in a volume about 0.035 m^3 . For the sake of simplicity, we have assumed a uniform distribution, even if this is not fully realistic, but it is sufficient for our purposes. Considering each atom singly ionized, we can now calculate the electron volume density n_e and, then, the Debye length λ_D and the plasma frequency ν (see Table I).

Electromagnetic interferences. – The physical meaning of the plasma characteristic parameters (λ_D and ν) is that electrons can move, with respect to ions, a distance λ_D in a time ν^{-1} , before an electric field is developed in order to restore the charge neutrality. Ions and electrons can be seen as electric dipoles, with distance λ_D , oscillating with a frequency ν . If we consider the microwave frequency limit of $\nu_{mw} = 3 \cdot 10^{11} \text{ Hz}$, we infer that a Leonid meteoroid with a mass up to 8 mg is sufficient to generate a plasma cloud with a characteristic frequency lower than ν_{mw} .

TABLE I. – *Examples of charge generation and plasma parameters for Leonids. For explanation of symbols, see the text.*

r [m]	Q [C]	n_e [m ⁻³]	λ_D [m]	ν [Hz]
10^{-4}	$2.8 \cdot 10^{-3}$	$5.0 \cdot 10^{17}$	$1.7 \cdot 10^{-5}$	$6.3 \cdot 10^9$
10^{-3}	3.2	$5.7 \cdot 10^{20}$	$5.0 \cdot 10^{-7}$	$2.1 \cdot 10^{11}$
10^{-2}	$3.7 \cdot 10^3$	$6.6 \cdot 10^{23}$	$1.5 \cdot 10^{-8}$	$7.3 \cdot 10^{12}$

The average power radiated by a dipole is well known from electromagnetic theory [10]. We assume that the field produced at distances $R \gg \lambda_D$ (far field condition) by a spherical dipole distribution, with λ_D as radius, is equivalent to the field of a point dipole with moment amplitude:

$$p = \frac{4}{3} \pi e \lambda_D^4 n_e \text{ [C} \cdot \text{m]} \quad (3)$$

where e is the electron charge [C]. For $\nu = \nu_{mw} = 3 \cdot 10^{11}$ Hz, we obtain $p = 1.2 \cdot 10^{-23}$ C·m. Then, the average power radiated is:

$$\langle P \rangle = \frac{p^2 \omega^4}{12 \pi \epsilon_0 c^3} \simeq 3 \cdot 10^{-13} \text{ [W]} \quad (4)$$

where $\epsilon_0 = 8.854187817 \cdot 10^{-12}$ F/m is the vacuum dielectric constant, c is the light speed in vacuum [m/s] and $\omega = 2\pi\nu$.

This value must be compared with the noise of satellite electronic devices. Below $6 \cdot 10^{12}$ Hz, the noise has a flat power spectral density of about $4 \cdot 10^{-21}$ W/Hz, that is -204 dB W/Hz [11]. If we consider a radar, which has a bandwidth of about 60 dB Hz, and other factors that make worse, the mean noise power in a receiver is about -146 dB W, that is $2.5 \cdot 10^{-15}$ W. Comparing these estimates with (4), we obtain an interference of at least *two order of magnitude greater than the electronic noise*. It seems clear therefore that the plasma can generate an electromagnetic interference that is not negligible and can disturb the regular satellite operations. For a specific example, if we consider the *International Space Station* (1000 m² area), exposed for 1 hour to a meteoroid flux like 1966 Leonids, there is 41% of impact probability with a meteoroid with mass equal or greater than 10^{-8} kg [12]. Such an impact flux can produce a sequence of interferences which can increase the noise level in electronic devices, then disturbing the regular satellite operations.

Conclusions. – After the *Olympus* end-of-life anomaly [2] and the work of McDonnell *et al.* [3], it seems clear that the meteoroids hazard is not restricted to a mechanical damage. Here it is suggested a new interference path, that is electromagnetic radiation emitted from the impact-produced plasma cloud. Even if the radiated power is not sufficient to destroy anything, it may disturb regular satellite operations. Further investigations should be made on specific satellite, because they require detailed information about onboard electronics, in order to calculate possible couplings and non-linearities.

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